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Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces

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Abstract

Modern office buildings often have large glazed areas. Incident solar radiation can lead to large cooling demands during hot periods although the solar radiation can help reduce heating demands during cool periods.

Previous studies have shown that large parts of the net energy demand of an office building is related to window heat loss and cooling demands induced by solar irradiance. In this article, the authors found that, even in what traditionally has been considered to be a heating-dominated climate, cooling demands dominate the net energy demand of an office building. Solar shading systems are vital to reduce the cooling demand of an office building.

Introducing shading systems might contribute to higher heating demands as well as higher demands for artificial lighting but at the same time it might be necessary in order to reduce glare issues.

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. Energy demands for heating, cooling, lighting and ventilation fans have been assessed. The simulations show that the choice of shading strategy can have an impact on the energy demand of the offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

In addition, the shading systems can contribute toward a lowered thermal transmittance value (*U*-value) of the window by functioning as an additional layer in the glazing unit when closed. Potential improvements of *U*-values have been studied in combination with the shading system's effect on solar heat gains and daylight levels. Experimental investigations of in-between the panes solar shading system effects on window *U*-values are currently being carried out at the Research Centre on Zero Emission Buildings (www.ZEB.no).

It was found that automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but that they should not be installed without a thorough case-by-case investigation as increased energy demands were found if an improper shading strategy was chosen. Upgrading to four-pane glazing will, however, always have a beneficial impact on the energy demand compared to two- and three-pane glazing.

Keywords: Solar shading; Heating demand; Cooling load; Daylight

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1. Introduction

1.1. The task at hand

Modern office buildings often have large glazed areas toward the exterior where the glazed parts of the building envelope can constitute a substantial part of the total area. This makes them especially exposed to and dependent on solar radiation, which can lead to large cooling demands during hot periods. However, the solar radiation can help reduce heating demands during hot periods. Thus, solar shading devices become important for optimizing and controlling solar radiation entering the offices.

Existing studies Dubois and Blomsterberg (2011) and Silva et al. (2012) have found that control strategies are not without flaws, making for higher real energy consumption than simulations have predicted. The sensitivity analysis performed in this work sheds light on how to better accommodate user behaviour in the design of shading control strategies and how to make the control strategies more robust, focusing on a cold climate.

Previous studies also show that large parts of the net energy demand of an office building is related to window heat loss and cooling demands induced by solar irradiance. In this study (Grynning et al., 2011), the authors found that even in what traditionally has been considered to be a heating-dominated climate, cooling demands dominate the net energy demand of an office building. Solar shading measures are vital for reducing the cooling demand of an office building.

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. The aim has been to optimize shading strategies and window properties in order to reduce energy demands for heating, cooling and artificial lighting while maintaining adequate thermal and visual comfort levels for the users. An additional intention of the study has been to investigate the reliability of commercially available software developed for the purpose of studying the performance of glazed façades.

1.2. Energy performance of shading systems – existing studies

As several previous studies have found, automatic control of shading is essential for realizing the energy-saving potential and daylight benefits of the shading systems. The control methods must simultaneously include both lighting and cooling energy demands (Kim et al., 2007). This should ideally be extended to also include heating energy. Control strategies must, in addition, be tailored to perform in its designated climate. The best strategy will vary greatly depending on the type of climate. Manual control should be avoided from an energy-saving point of view because users of the buildings tend to leave the blinds either open or closed regardless of what is optimal with respect to cooling/heating need and or daylight levels (Reinhart and Voss, 2003; Nielsen et al., 2011). However, it should be noted that user preferences often contradict such automatic systems. Studies regarding user behaviour and occupant preferences (Stevens, 2001; Galasiu and Veitch, 2006; Thunshelle and Hauge, 2012) have found that occupants tend to prefer manual control and the possibility to override automatic systems. Regardless of this, it is important to investigate and optimize automatic controls, which is why the authors chose to focus on the automatic control systems in this work.

Furthermore, the choice of strategy is important in order to optimize the use of solar gains. Several studies have been performed where control strategies and patterns of various shading systems have been studied (Tzempelikos and Athienitis, 2007; Koo et al., 2010; Appelfeld et al., 2012; Goia et al., 2013). In van Moeseke et al. (2007) it was found that in order to reduce heating demands during winter, a combination of solar irradiance levels and internal temperature set points should be used. This will ensure better utilization of solar gains for heating during wintertime.

1.3. Overview of key performance and assessment parameters

Several aspects must be considered in order to fully understand the performance of the glazed parts of a façade. In addition to the energy use for heating, cooling and lighting, visual comfort must also be satisfactory in order to classify a system as performing well.

1.3.1. Daylight and solar heat gains – effect on cooling and heating demand

Overheating is a major concern for modern office buildings, even in cold climates. Thus, solar shading systems must be introduced in these buildings in order to reduce the energy demand for cooling. A properly designed shading system must, however, handle several important issues.

1.3.2. Daylight, visual transmission – illuminance levels and artificial light

In order to maximize the use of daylight, a high visible transmittance factor (T_{vis}) is desirable.

Previous studies state that large energy savings can be found through optimization of the artificial lighting design A lowered lighting power density (LPD) has two major benefits: reducing the energy demand for lighting and reducing the internal loads, thus contributing to lowering the office's cooling demands.

Detailed studies of offices show that energy consumption for lighting can be more than halved by using modern, controlled systems. This corresponds to the findings by Bülow-Hübe (2001), where the author found that electricity demand for an office building in Gothenburg could be reduced from 23 kW h/m^2 year to 11 kW h/m^2 year. LPD levels of modern offices should, according to the European standard NS-EN 15193 *Energy performance of buildings – Energy requirements for lighting* (NS-EN, 2008), be aimed at reaching 8 W/m^2 for normal offices. The Norwegian standard for energy calculations, NS 3031 *Calculation of energy performance of buildings – Method and data* (NS, 2011), takes it one step further by stating that a yearly average LPD of 5 W/m^2 is sufficient to ensure adequate lighting levels in low-energy and passive house standard offices; however, the reason for this low level is not clarified in the standard. In this work, a choice has been made to keep the NS-EN 15193 LPD level of 8 W/m^2 for the simulations performed. The choice was based on the unfounded description of LPD levels in the NS 3031 standard and the fact that NS-EN 15193 is an international standard and is therefore likely to give a more general representation of LPD levels.

1.3.3. Thermal transmittance of glazing units with in-between shading

An in-between pane type of shading system will influence the thermal transmittance value of the glazing system. When the shading slats are closed, it can function as an additional layer in the glazing unit. On the one hand, this might reduce the *U*-value of the glazing system; on the other hand, an increase in the *U*-value is anticipated when the slats are in the open position, making them into thermal bridges between the hot and cold side of the cavity (Tzempelikos, 2005). The additional hardware that needs to be mounted in the glazing cavity will also contribute to a higher *U*-value of the glazing unit. Experimental investigations are currently being performed as part of the work carried out by the Research Centre on Zero Emission Buildings (www.ZEB.no).

1.3.4. Daylight – glare indexes and visual comfort

The glare index (GI) is, in this context, used to estimate the amount of discomfort glare caused by the windows in an office space. The GI factor is basically a quantified index that describes the difference between the luminance of an object in relation to the luminance of interior surfaces surrounding the window, as seen from a reference point (Hopkinson, 1972). Several correlation formulae have been proposed throughout the last 40–50 years (Osterhaus, 2005).

The discomfort glare index (DGI) is related to set levels of the GI where human perception of the glare takes on different forms. The degree of discomfort is measured in terms of reduced performance of a given task. The DGI limits for office work as defined in the EnergyPlus software manual (EnergyPlus, 2012) are shown below.

- 16: Just perceptible.
- 20: Just acceptable.
- 22: Borderline between comfort and discomfort.
- 24: Just uncomfortable.
- 28: Just intolerable.

This corresponds to NS-EN ISO 12464-1:2011 – *Light and lighting – Lighting of work places – Part 1: Indoor work places* (NS-EN, 2011), where the boundary for acceptable GI is set at 22. However, it is important to be aware that there are uncertainties regarding how glare is perceived. This could be caused both by calculation procedures of the DGI as well as differences in human perception of glare (Bellia et al., 2008).

Based on these limiting values for the DGI, adjustments can be made to a solar shading system control strategy in order to stay below certain glare levels. However, it should be noted that an in-between glazing shading system might not be the most efficient system for handling glare. Internal shades or curtains manually operated by the user could be considered as a low-tech but efficient solution for reducing unwanted glare, especially during winter when solar radiation can provide useful gains in terms of reducing the heating demand.

Daylight illumination levels are also important in helping to reduce the need for artificial light. Daylight is thought to have beneficial impacts on humans, including improving work efficiency. Nabil and Mardaljevic (2006) found, after an extensive literature review, that daylight illuminance levels are beneficial when in the range of 100–2000 lux. The maintained illuminance level for a workspace should, according to standard NS-EN 12464–1:2011 (NS-EN, 2011), be higher than 500 lux. Reinhart and Weissman (2012) carried out a study where 60 architectural students made subjective assessments of the daylight quality in a room. Their assessments were compared to some of the most common daylight metric methods and levels found in the literature. They found that a target illuminance level of 300 lux or more coincided with what the students considered to be a well daylit room. The traditional daylight factor did not align so well with the assessment of the daylit space.

A description of the assessment methods used in this work is presented in Section 2.2.1.

1.3.5. Thermal comfort – Fanger's model

Thermal comfort is assessed using the Fanger comfort model (Fanger, 1967). Fanger's model is based on an energy analysis that accounts for all the modes of energy loss from the body. The model encompasses air and mean radiant temperature along with the applicable metabolic rate, clothing insulation, air speed and humidity to predict thermal comfort. The heat balance is combined with experimentally derived physiological parameters in order to predict the thermal sensation and the physiological response of a person due to their environment. This is quantified here as the Predicted Percentage of Dissatisfied people (PPD). A thorough description of the model can be found in the simulation tool description (EnergyPlus, 2012).

2. Simulations

2.1. Methodology – software description and limitations

This article presents a solar shading strategy parameter study for an office cell. Different shading strategies for in-between pane shading systems in various single- and two-person office spaces have been performed. Solar shadings are vital in controlling the input of solar radiation in offices; the two typologies of office cells were chosen in order to give a better representation of typical office cubicles. A room-level study was chosen in order to reduce simulation time and at the same time get a thorough investigation of the integral situation including energy demands, thermal comfort and daylight availability in the offices.

Simulations have been carried out using the numerical simulation tool COMFEN 4.1, 2012. The program is a graphical user interface tool that uses the EnergyPlus 7.0 building energy simulation program (EnergyPlus, 2011) for the underlying simulations. The software tool has been developed to carry out comparative studies of integrated energy and daylight simulations of single-zone models, for example office spaces, emphasizing detailed modelling of glazed parts of the façades. However, users should be aware of some limitations of the software, for example restrictions in the positioning of the between-glass shading layers as the default places it in the innermost cavity of a triple-pane window. This is a limiting factor if one is modelling systems where shadings might be placed in the outermost cavity. In addition to this, modelling of windows with four or more panes is not possible in combination with shading layers.

Daylight levels and the corresponding energy demand for artificial light have been studied in combination with the heating and cooling energy demands as well as energy demand for operating circulation fans in the ventilation system of the office cell.

The cooling system was sized according to the peak demand for the office cell on a typical summer day. A separate simulation of the cooling demand for the office cell was done to confirm the size of the system. The necessary air volume and flow rate of the fan was calculated. An increase in cooling demand leads to the need for a larger (more power-consuming) fan. Based on this, the energy demands for fans were considered as part of the cooling-related energy demands of the cases studied.

The window properties have been calculated using detailed spectral data of actual (real) glazing and shading layers. Input values for the various layers have been taken from the International Glazing Database (IGDB) and the Complex Glazing Database (CGDB), both of which were developed and continue to be maintained by Lawrence Berkeley National Laboratories (LBNL, 2012).

2.2. Office case description

Simulations have been performed for one- and two-person office cubicles. The main characteristics of the office cells are given in Table 1. A graphical illustration of the office cubicles is shown in Fig. 1. The windows studied are two-pane windows with a *U*-value of 1.4 W/m^2 K, three-pane windows that fulfil the Norwegian passive house standard NS 3700, *Criteria for passive houses and low energy houses – Residential buildings* (NS, 2010), with a *U*-value lower than 0.7 W/m^2 K and a state-of-the-art four-pane window with a *U*-value of 0.45 W/m^2 K. Three window-to-wall ratios (WWR) have been studied: 41%, 51% and 61%. A HVAC system that delivers the theoretical loads necessary to keep temperatures within the heating and cooling set point temperatures are used in the simulations.

Table 1
Description of office cell geometry and gains.

Single person cubicle and two-person office space	
Climate	Oslo (N 59°54′ E 10° 27′) Yearly mean temperature = 6.7 °C
Façade area (width × height)	3 × 3 m = 9 m^2
Façade *U*-value (opaque part)	0.15 W/m^2 K
Room depth	
Single-person cubicle	3.5 m
Two-person office cell	6.0 m
Heated floor area	
Single-person cubicle	10.5 m^2
Two-person office cell	18.0 m^2
Window dimensions	
2 each 1.28 × 1.43 m (width × height)	3.7 m^2 (41% WWR)
2 each 1.28 × 1.80 m (width × height)	4.6 m^2 (51% WWR)
2 each 1.28 × 2.15 m (width × height)	5.5 m^2 (61% WWR)
Window properties	2-, 3- and 4-pane window (see Table 2 for specs)
Shading strategies	11 strategies (see Table 3 for description)
Internal gains	For schedule description, see Section 2.2.2
Equipment	6 W/m^2 (NS, 2012)
Lighting (daylight continuous dimming)	8 W/m^2 (see Section 1.3.2)
Single-person cubicle	1 occupant (activity level: *office work*)
Two-person office	2 occupants (activity level: *office work*)
Daylight illumination reference point location	See Section 2.2.1

2.2.1. Daylight illumination and glare set point levels

Daylight illumination level set points for activating artificial lighting are set to 50 foot-candles, equalling 538 lux. If the illumination levels drop below this, artificial lighting is switched on. A maximum allowable GI (as described in Section 1.3.4) is set to 22. This corresponds to a level on the border between comfort and discomfort, where values lower than 22 indicate comfort. Glare indexes are based on a glare view angle perpendicular to the façade, i.e. the sensor is facing one of the side walls of the office. The sensors are placed as illustrated in Fig. 2, as per the simulation tool's default. In the two-person office space, the floor area is divided into two zones: a primary daylight zone closest to the façade and a secondary zone toward the back of the

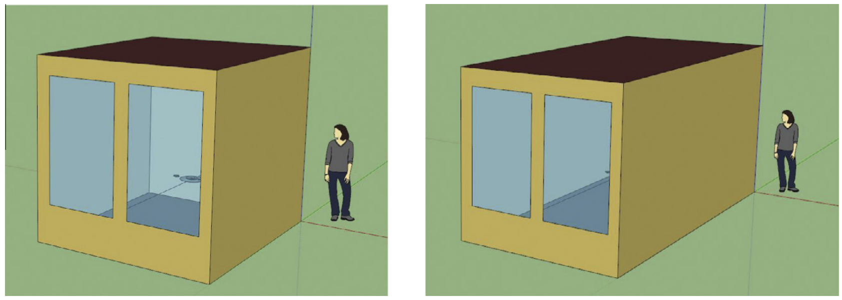

Fig. 1. Illustration of the two office cell geometries. Single-person cubicle shown on the left and two-person office cell on the right.

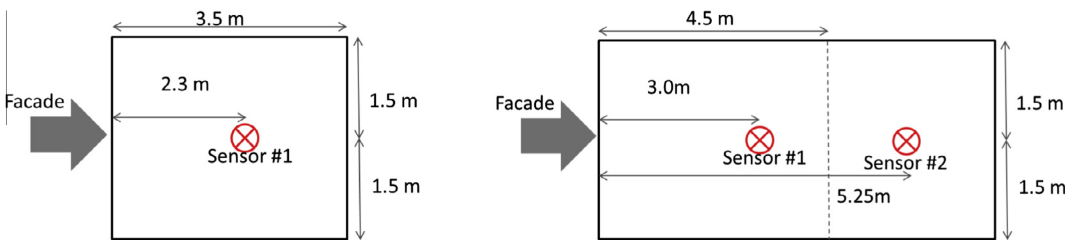

Fig. 2. On the left: illustration showing the placement of the daylight sensor in the single-person cubicle. On the right: illustration showing the placement of the daylight sensors in the two-person office space.

office space. Two sensor positions are used: sensor #1 controls the primary zone, which constitutes 75% of the floor area; sensor #2 controls the secondary zone covering the remaining 25%. As per the simulation tool's default, the primary zone sensor is positioned 2/3 of the primary daylight zone depth from the façade wall. The secondary zone sensor is by default placed in the centre of the zone. All sensors are positioned at desk height, 0.76 m above the floor. Continuous dimming functions for the artificial lighting system have been used.

Based on the discussion in Section 1.3.4, daylight illumination levels were used to assess the quality of the daylight in the rooms. Both the 100–2000 lux interval and the threshold illuminance of 300 lux were studied. This parameter was chosen rather than calculating daylight factors because it was found that it gave a better representation of actual daylight qualities in the offices studied.

2.2.2. Schedules

Default schedules for lighting, occupancy and equipment defined in the COMFEN (Mitchell et al., 2011) were used. Main operational hours are between 08.00 and 18.00 on weekdays. The schedules could not be altered in the software. Continuous lighting controls were used for the artificial light.

2.2.3. Window properties – two-, three- and four-pane windows

A double- and a triple-pane glazing unit with in-between pane venetian blinds have been studied. A four-pane window without shading has been included for further comparison. The glazing units' main characteristics of solar heat gain coefficient (SHGC), visible transmission coefficient (T_{vis}) and thermal transmittance (U-value) are shown in Table 2. The frames have been kept the same, with a U-value of 1.3 W/(m^2 K) for all the studied windows.

2.2.4. In-between pane venetian blinds – shading strategies and material properties

The shading systems studied are all a horizontal type venetian blind. Aluminium with thermal conductivity λ of 159 W/(m K) and surface emissivity of 0.9 have been used as slat material.

There are 20 predefined strategies for solar shading system controls available in COMFEN. A number of them can be customized by adjusting set point levels for solar irradiance, temperatures, etc. Six of these shading strategies, as shown in Table 3, have been chosen for further studies. A twelfth case with no shading has been included as a reference. The shading strategies were chosen in order to investigate three main principles for shading control:

- Reduce cooling demands.
- Improve visual comfort (reduce glare) and
- Reduce heat loss during the night using night-time shading.

Shading strategies 1 and 2 were chosen to represent cases where the shading is activated based on cooling demands. Strategy 3 is based on using the shading devices only for glare-reducing (i.e. daylight comfort) purposes. Strategies 4–6 were chosen in order to study if any beneficial effects of the shading devices to the thermal insulating properties of the glazing units could be found. Strategy 4 represents a case where the shading is used only during the night if there is a heating demand in the office space.

Table 2
Description of glazing units without shading layer and their key performance parameters used in the simulations.

Window	Layer-by-layer description[a]	SHGC (–)	T_{vis} (–)	U-value glazing (W/m^2 K)
2-pane window	4-29Ar-E4, $e = 0.013$, 95% argon	0.479	0.711	1.453
3-pane glazing	4-16Ar-E4-29Ar-E4, $e = 0.013$, 95% argon	0.375	0.579	0.686
4-pane glazing	4E-12Ar-4E-12Ar-4-12Ar-E4, $e = 0.013$, 95% argon	0.278	0.478	0.452

[a] The layer-by-layer description in the second column describes the following. The first number denotes the thickness of the exterior glass pane. The capital E indicates if a low-e coating is applied to the pane. An E in front of the digit indicates that the low-e coating is applied on the exterior side of the glass pane and vice versa if it is placed on the interior side. The second number (after the first hyphen) denotes the thickness (in mm) of the cavity behind the outer glass pane and if it is gas-filled. The Ar index indicates that argon is used as a gas filling. The third number (after the second hyphen) shows the thickness (and if there is any low-e coating) of the second pane. The fourth number shows the next cavity and so on for the fifth and following numbers.

Table 3
Overview of shading strategies studied.

Main shading strategy	Parameter set point	(a) Fixed slat angle	(b) Variable slat angle
No shading	–	Yes	–
Shade 1: activated if high zone air temperature	$T_{set} = 26$ °C	Yes	Yes
Shade 2: activated if high zone cooling	$P_{set} = 1$ W	Yes	Yes
Shade 3: activated if high glare	DGI = 22	Yes	–
Shade 4: activated at night if heating/off during daytime	$P_{set} = 1$ W	Yes	Yes
Shade 5: activated at night if low outside temperature/on during the day if cooling	$T_{set} = 26$ °C $P_{set} = 1$ W	Yes	Yes
Shade 6: shading activated at night if heating/on during the day if cooling	$P_{set} = 1$ W	Yes	Yes

Strategy 5 is similar but control is based on outside temperatures and includes use of shading during the daytime as well. Strategy 6 is similar to strategy 4, but here the shading is used during the day if cooling demands are also present.

In order to study the effect of variable blind angles, two cases have been studied for each of the strategies. The first case (denoted as shading strategy #a) is with a fixed slat angle where the slats are closed when shading is activated. In the second case (denoted as shading strategy #b), a cut-off strategy is used. The angle is adjusted in each simulation time-step to optimize the shade effect. A cut-off strategy like this will maximize available daylight levels. For the glare control case, only the variable slat angle option has been included. The parameter set points are shown in Table 3, where T_{set} is a temperature-based set point and P_{set} is based on incident solar radiation (in Watts).

3. Results and discussion

3.1. South-facing façades

The simulation results for the south-facing office cubicle façades are shown in Figs. 3–5 as well as in Tables 4 and 5.

The distribution of heating, cooling, lighting and fan-operation energy demands of the two-pane cases with WWR of 41% and 61% are shown in Fig. 3. The distribution for the cases with three-pane windows shows the same relative distribution for heating, cooling, lighting and fan energy demands as for the two-pane windows, and these figures are thus omitted here. Energy demand for running fans is correlated with the cooling demand, and should therefore be considered as part of the cooling-load demand. Looking at Fig. 3, one can observe that the heating demand is the dominating factor of the total demand. The combined cooling and fan load is the second largest element. Furthermore, one can see that increasing the window size from 41% to 61% in the offices increases the cooling loads, whereas the heating demands decrease slightly. This is the case for both the single-person cubicle and the two-person office. In general, one can see that a trade-off between cooling and heating-related demands is present for all shading strategies. The no-shade and shading strategy 1 cases have the lowest heating demand, but the cooling-related demands are high. Choosing one of the other strategies will lead to an increase in heating demand. This is as expected because the solar gains will be reduced.

3.1.1. Single-person cubicle offices

Even though the cooling and fan-operating demands are reduced for all strategies except for 4 and 4b, the increase in heating and lighting demands overcompensates for this and leads to a higher total energy demand. The negative impact is most pronounced for strategies 2, 2b, 6 and 6b. Thus, this research highlights that a shading system should not be installed without a thorough investigation in each case.

Fig. 4 and Table 4 shows that the potential for energy saving is dependent on office size as well as window properties. It is noted that unshaded windows are never the worst performer for any of the WWR situations. Savings potentials for two- and three-pane glazing with 41% WWR as well as three-pane glazing for the 51% and 61% cases were found to be approximately 1–2% compared with unshaded windows. For these façade configurations, the energy-saving potential for the office cell when installing shading compared to an unshaded window is insignificant.

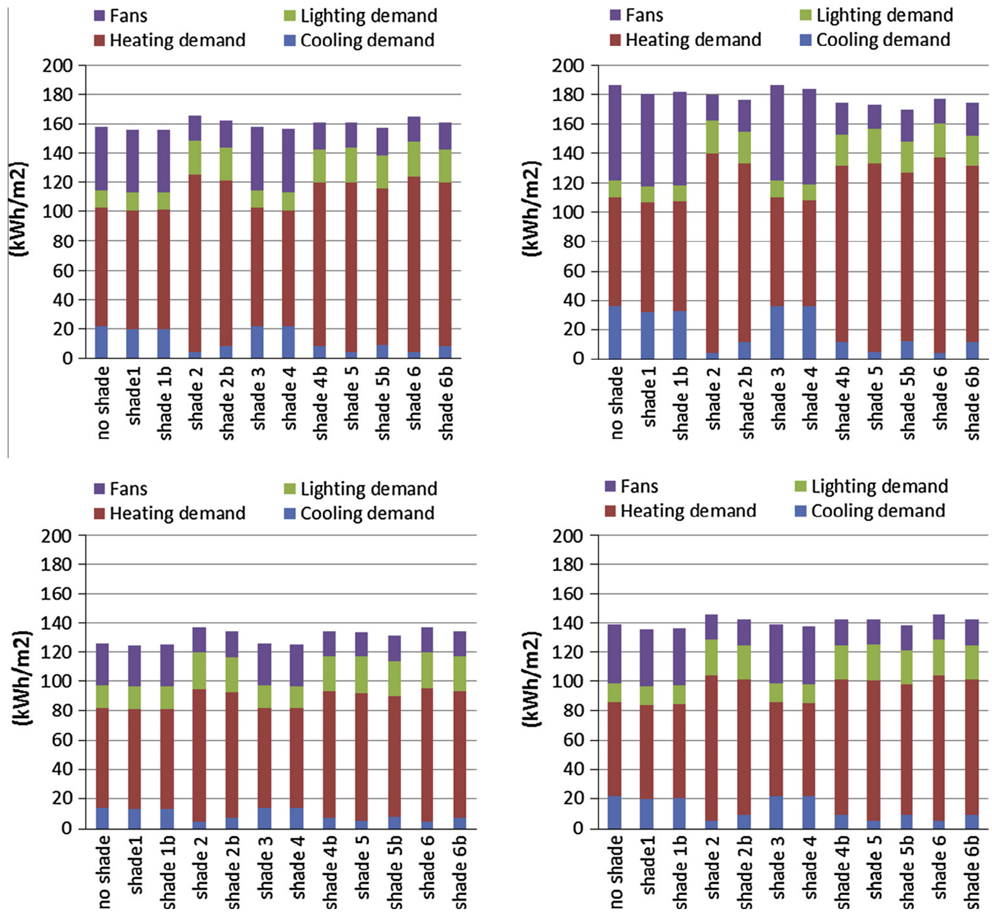

Fig. 3. Energy demand for heating, cooling, lighting and ventilation fans (kW h/m^2 heated floor area) for south-facing offices. Upper-left graph shows the two-pane 41% WWR single-person cubicle; the upper-right graph shows the two-pane 61% WWR single-person cubicle; the lower-left graph shows the two-pane 41% WWR two-person office; the lower-right graph shows the two-pane 61% WWR two-person office.

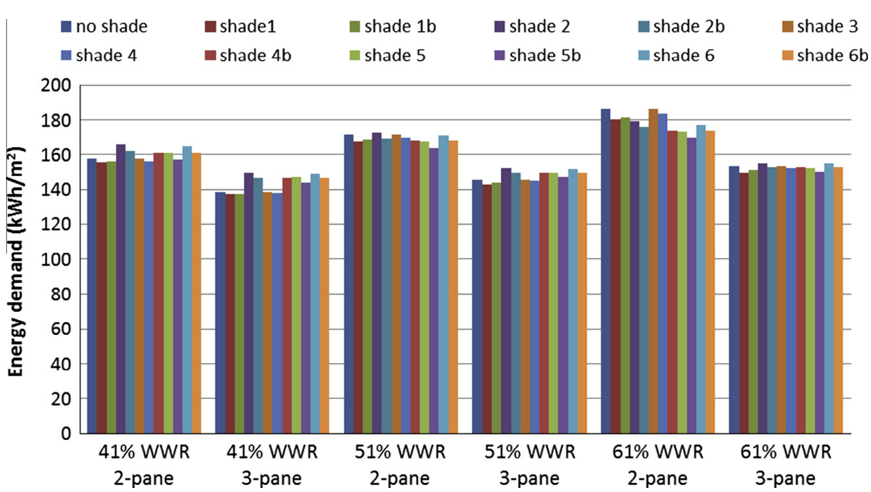

Fig. 4. Net energy demand of single-person cubicles with south-facing façades for the different shading strategies.

Two-pane glazing with a WWR of 51% show energy demand reduction potential of 5% compared to the unshaded case if shading strategy 5b is chosen. The double-pane glazing in a façade with 61% WWR shows an energy demand reduction potential of approximately 9% compared to unshaded windows when implementing a control strategy where the shading is activated during the night when temperatures are lower than 26 °C and during the day if there is a cooling demand in the office cell.

Furthermore, it can be seen that using the shading device only to reduce night-time heat losses (shading strategy 4 and 4b) has some impact. In some cases, the energy

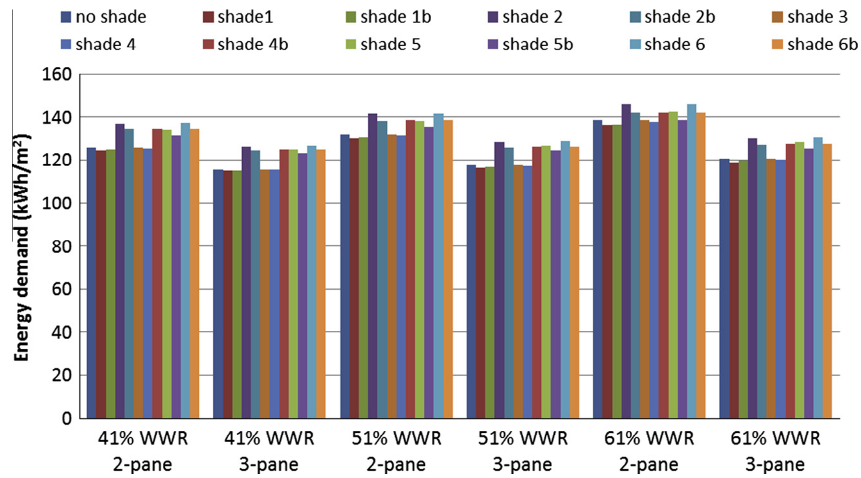

Fig. 5. Net energy demand of two-person offices with south-facing façades for the different shading strategies.

Table 4
Total net energy demand (kW h/m^2) for south-facing, single-person cubicles. The option with the lowest demand is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for south-facing, single-person cubicle						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	158	139	172	145	186	153
Shading strategy 1	156	137	168	143	180	150
Shading strategy 1b	156	138	168	144	182	151
Shading strategy 2	166	150	173	152	179	155
Shading strategy 2b	162	146	169	150	176	153
Shading strategy 3	158	139	172	145	186	153
Shading strategy 4	156	138	170	145	184	153
Shading strategy 4b	161	146	168	150	174	153
Shading strategy 5	161	147	167	150	173	152
Shading strategy 5b	157	144	164	147	170	150
Shading strategy 6	165	150	171	152	177	155
Shading strategy 6b	161	146	168	150	174	153
4 pane, no shading	134		138		142	

demands increase; however, the largest energy demand reduction can be seen for the 61% WWR case with two-pane glazing. Here, the energy demand is reduced by 6% compared to the unshaded configuration.

The four-pane window has the lowest energy demand for all window sizes compared to any of the shaded or unshaded configurations of the two- and three-pane windows.

The use of a four-pane glazing yields significant reductions in the energy demand compared to the unshaded windows with the following configurations:

- 15% reduction compared to the two-pane 41% WWR.
- 20% reduction compared to the two-pane 51% WWR.
- 24% compared to the two-pane 61% WWR.
- 5% compared to the three-pane 51% WWR and
- 7% for the three-pane 61% WWR.

Furthermore, it was found that an erroneous choice of shading strategy can lead to an increase in energy demand. The effect is largest for the three-pane 41% WWR, which shows an increase of 8% compared to unshaded windows if shading strategies 2a, 2b, 6a or 6b are chosen.

Placing the shading units in the outermost cavity of the three-pane glazing units will probably shift the energy demands to a certain extent. This should be investigated by performing comparative studies with similar in-between shading devices placed in the outer cavity.

Table 5
Total net energy demand (kW h/m^2) for south-facing, two-person offices. The option with the lowest demand for each office type is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for south-facing, two-person offices						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	126	116	132	118	139	121
Shading strategy 1	125	115	130	117	136	119
Shading strategy 1b	125	115	130	117	137	120
Shading strategy 2	137	126	142	128	146	130
Shading strategy 2b	134	124	138	126	142	127
Shading strategy 3	126	116	132	118	139	121
Shading strategy 4	125	115	131	117	138	120
Shading strategy 4b	135	125	139	126	142	128
Shading strategy 5	134	125	138	127	142	128
Shading strategy 5b	131	123	135	124	139	126
Shading strategy 6	137	127	142	129	146	130
Shading strategy 6b	135	125	139	126	142	128
4 pane, no shading	115		115		116	

3.1.2. Two-person offices

As can be seen from Fig. 5 and Table 5, the relative energy-saving potential on a per m^2 basis when using shading systems compared to unshaded windows is even lower for the two-person office than for the single-person cubicle. This is as expected as the relative floor to façade area increases compared to a single-person office.

For all the two- and three-pane windows and shading configurations, the savings potentials are around 1–2% and can therefore be considered insignificant.

Compared to the three-pane glazing units, upgrading to four-pane glazing yields energy savings of approximately 1–4%. The four-pane window still has the lowest energy demand for all window sizes compared to any of the shaded or unshaded configurations of the two- and three-pane windows.

As for the single-person cubicle, an erroneous choice of shading strategy will lead to an increase in the total energy demand. The effect is largest if shading strategy 6 is chosen for the three-pane 41% WWR case, with a 10% increase in energy demand compared to unshaded windows.

For the two-person office, using the shading device only to reduce night-time heat losses (shading strategy 4 and 4b) has some effect. However, in most cases it will lead to an increase in energy demand compared to the unshaded cases. Contrary to the single-person office space, no reduction was found for the 61% WWR case with two-pane glazing using shading strategy 4b; instead, the energy demand was found to increase by 2%.

The use of four-pane glazing yields significant reductions in the energy demand compared with the following configurations:

- 9% reduction for the two-pane 41% WWR.
- 13% reduction compared to the two-pane 51% WWR and
- 16% for the two-pane 61% WWR.

An increase of the window area will, for all simulation cases, lead to a higher energy demand for the offices.

3.2. North-facing façades

3.2.1. Single-person cubicles

As shown in Table 6, the simulations show that the savings potentials for these façades when shading systems are used are low. A best-case saving was found for the two-pane 61% WWR, with an energy demand reduction of 2%, which is still insignificant. Switching to four-pane glazing will yield energy demand reductions. Replacing two-pane with four-pane glazing reduces energy demands by 12–18%; replacing three-pane with four-pane glazing gives reductions close to 1%.

Furthermore, the simulations show that the wrong choice of shading strategy can lead to an energy demand increase compared to unshaded windows. The effect was found to be largest if shading strategy 2, 2b, 4, 6 or 6b is chosen for the three-pane 61% WWR case, with a 6% increase in energy demand compared to unshaded windows.

3.2.2. Two-person offices

As seen in Table 7, the simulations show that savings potentials for these façades when including shading systems are low for two-person offices with north-facing façades. A best-case saving was found for the two-pane

Table 6
Total net energy demand (kW h/m^2) for north-facing, single-person cubicles. The option with the lowest demand is highlighted in green; the worst-performing option is highlighted in red.

Net energy demand (kWh/m^2) for north-facing, single-person cubicle						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	170	152	178	155	187	159
Shading strategy 1	169	152	177	154	185	158
Shading strategy 1b	169	152	177	155	186	158
Shading strategy 2	177	158	186	162	195	167
Shading strategy 2b	177	159	187	163	195	167
Shading strategy 3	170	152	178	155	187	159
Shading strategy 4	168	152	176	154	184	157
Shading strategy 4b	176	158	184	163	192	167
Shading strategy 5	171	155	180	160	187	163
Shading strategy 5b	172	156	180	160	188	164
Shading strategy 6	175	158	184	162	192	167
Shading strategy 6b	176	158	184	163	192	167
4 pane, no shading	150		152		154	

Table 7
Total net energy demand (kW h/m^2) for north-facing, two-person offices. The option with the lowest demand for each office type is highlighted in green; the worst-performing option is highlighted in red.

North-facing façades, two-person offices						
	41 % WWR 2-pane	41 % WWR 3-pane	51 % WWR 2-pane	51 % WWR 3-pane	61 % WWR 2-pane	61 % WWR 3-pane
No shading	140	129	144	131	148	132
Shading strategy 1	139	129	143	130	147	131
Shading strategy 1b	139	129	143	130	147	132
Shading strategy 2	143	132	149	135	155	137
Shading strategy 2b	143	132	149	135	155	138
Shading strategy 3	140	129	144	131	148	132
Shading strategy 4	139	129	143	130	147	132
Shading strategy 4b	143	132	149	135	155	138
Shading strategy 5	140	130	146	133	151	136
Shading strategy 5b	140	131	146	133	151	136
Shading strategy 6	143	132	149	135	155	138
Shading strategy 6b	143	132	149	135	155	138
4 pane, no shading	127		129		130	

61% WWR, with an energy demand reduction of 1%, which is insignificant. Switching to four-pane glazing will yield energy demand reductions. Replacing two-pane with four-pane glazing reduces energy demands by 9–12%; replacing three-pane with four-pane glazing gives reductions of less than 1%.

The energy-saving potential when installing shading systems is minor. Many of the shading control strategies will yield higher energy demands than an unshaded window. The energy demand increase was found to be largest if shading strategy 2b, 4b, 6 or 6b is chosen for the three-pane 61% WWR case, with a 5% increase in energy demand.

Table 8
Key daylight and thermal comfort performance data for south-facing single-person offices with two-pane glazing. The unshaded and the shading alternative with the lowest energy demand for each of the WWRs are shown.

	41% WWR		51% WWR		61% WWR	
	Unshaded	Best performer 1b	Unshaded	Best performer 5b	Unshaded	Best performer 5
Average GI (GI_{avg})	5	4	5	1	5	1
Hours when GI > 22	115	113	115	17	115	15
Hours when illumination > 300 lux	2613	2476	2926	681	3108	924
Hours when daylight illumination is in the range of 100–2000 lux	3086	2997	2790	1954	2582	1347
Average illumination level due to daylight (lux)	487	462	680	144	904	165
Thermal comfort, Fanger average PPD (%)	18	18	18	21	18	25

3.3. Daylight, glare and thermal comfort

3.3.1. South-facing façades

Table 8 shows key lighting data for south-facing single-person cubicles with two-pane glazing. The unshaded façades are compared to the shading strategy with the lowest energy demand. It is obvious that the introduction of a shading system that minimizes energy demands will influence the daylight and glare levels in the offices. The effects are most pronounced for the largest WWR. The effects are, however, twofold: the GI will be reduced and the hours when the GI is above 22 are reduced significantly. For the 61% WWR, the number of hours when glare is above the limit of 22 will be reduced by 90% when installing a shading system. However, the average yearly daylight levels will be reduced to approximately 80% compared to an office with unshaded windows.

The thermal comfort is not significantly altered as a function of the shading strategies, as shown in Table 8. The PPD is constant regardless of window size and shading strategy except for one case. The case where a notable change occurs in the PPD is the 61% WWR case. The PPD increases from 18% to 25% when switching from unshaded windows to shading strategy 5. The increase in the PPD when switching to shaded windows mainly occurs in the period from early May to mid-September. This is somewhat counter-intuitive as one should expect that adding shading would improve the thermal comfort during the warm period of the year due to better control of solar insolation. The algorithm used for assessing thermal comfort according to the Fanger method is a function of the mean radiant and air temperature, among other elements (EnergyPlus, 2012). It was found that the yearly average mean radiant temperature for the office using shades was higher than for an unshaded office. This is not as expected and is caused by higher window interior surface temperatures with blinds closed. It is likely a result of how the software tool treats the absorption and reflectance properties of the opaque slats in the shading device. It seems that absorption of solar energy in the shading slats is overestimated and gives an improbable temperature increase. This will spread further inwards in the glazing unit and the temperature of the interior glass pane will ultimately increase. One should therefore treat the thermal comfort simulation results using Energy Plus ver. 7.0 with care and any conclusions without further investigations of the algorithm could not be drawn. Measurements on systems should be carried out in order to verify the behaviour of such shading systems.

3.3.2. North-facing façades

Simulations show that north-facing offices will not meet current standards and demands for daylight levels. The best-case scenario, with the highest daylight levels, is with an unshaded two-pane glazing and a WWR of 61%. This particular office cell will have an average daylight illumination level at sensor 1 of 236 lux. Furthermore, it was found that the daylight illumination level is higher than 300 lux during 2775 h of the year for this configuration.

The simulations also show that for north-facing façades, glare issues will never be a problem due to direct solar radiation. This is the case even for an unshaded façade with two-pane glazing and a WWR of 61%, which has a maximum GI of 12. Reflections from neighbouring buildings could, however, be a problem. Shading devices designed only for glare reduction should therefore be considered in such cases.

4. Discussion and conclusions

Simulations of a number of shading strategies have been performed for south- and north-facing office cubicles with varying floor areas, window sizes and window parameters. Energy demands for heating, cooling, lighting and ventilation fans have been assessed. The simulations show that the choice of shading strategy can have an impact on the energy demand of the offices. Depending on strategy, the energy demand can either increase or decrease compared to an unshaded one- or two-person office cubicle.

North-facing offices were found to have larger energy demands than south-facing offices, mainly due to higher heating demands. Lighting energy demand is also slightly higher for north-facing offices. The use of shading systems has insignificant potential for reduction of energy demands on north-facing façades. On the contrary, it can potentially lead to an increase in energy demands of as much as 5% if an improper strategy is used. Shading systems should therefore not be used on north-facing façades of small- or medium-sized office cubicles. Using four-pane glazing will, however, reduce the energy demand compared to windows with two- or three-pane glazing. Other aspects such as color rendering due to a thick glass layer must be addressed in order to ensure good visual quality of the spaces. Using low-iron glass could be one of the technical solutions for this.

The simulations also show that glare issues will never be a problem for north-facing façades. The GI level for any of the north-facing façades never exceeded 12.

In contrast to the north-facing façades, the results show that there is potential to reduce energy demands for the south-facing façades. Energy demand reductions can be as large as 9% if the right shading strategy is chosen. However, as for the north-facing offices, it was found that improper use of shading systems will lead to an increase of the total energy demand. This increase in energy demand can be as high as 10%.

Thus, it can be concluded that automatically controlled shading systems can reduce the energy demands of south-facing, small office cubicles, but they should not be installed without a thorough investigation in each single case.

Upgrading to four-pane glazing will always have a beneficial impact on the energy demand compared to two- and three-pane glazing. Energy demand reductions can be as high as 20% if two-pane glazing is replaced with four panes. If a three-pane window is interchanged with a four-pane glazing unit, energy demand reductions were found to be as high as 7%. Glare problems must however be addressed and reduced to an acceptable level; this will not be achieved with unshaded façades. The location of glare-reducing measures is not limited to in-between glazing pane shading units; both internal and external shading devices can be utilized.

5. Further work

Simulations have been performed for shading systems placed in the innermost cavity of the glazing units. Future studies should investigate the effects of shading systems placed in the outermost or other internal cavities of the glazing units as well as externally placed shading systems. Four-pane glazing in combination with in-between or external shading systems should also be studied. Further studies should also be carried out where the performance of shading systems is assessed on the whole building level. Optimization algorithms for thermal as well as optical performance of shading systems should be established in order to make guidelines that are useable in the early stage planning of offices and office façades.

Measurements of component performance as well as room and whole building performance should be carried out with the purpose of validating the simulations.

The thermal comfort situation for different shading strategies is of utmost importance for a building. The simulation results for thermal comfort were ambiguous and should therefore be treated with care and further investigation of simulation procedures should be completed.

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